Pressure transient analysis to inform design for building and roof drainage systems

Citation for published version:
Swaffield, J, Wright, G & Arthur, S 2004, Pressure transient analysis to inform design for building and roof drainage systems. in *Proceedings of the 9th BHR International Conference on Pressure Surges.*

Published In:
Proceedings of the 9th BHR International Conference on Pressure Surges

Pressure transient analysis to inform system design for building and roof drainage systems

Prof. J.A. Swaffield, Dr G.B. Wright, Dr L.B. Jack and Dr S. Arthur
School of the Built Environment, Heriot Watt University, Edinburgh, Scotland.

SYNOPSIS

The transient analysis of the fluid services associated with building operation is necessary due to the growing complexity of the built environment, and the need to both simplify system design and accommodate climate change. The prevention of odour ingress and cross contamination between habitable spaces via the drainage network is essential. It is also vital to ensure that siphonic roof drainage systems are dynamically balanced and that pressures do not drop to dangerously low levels. In these cases, transient analysis can be employed to improve system design and to determine the causes of operational problems and system failures.

NOTATION

A	Flow cross sectional area, *m^2*
c	Acoustic wave velocity, *m/s*
D	Pipe diameter, *m*
f	Friction factor
g	Acceleration due to gravity, *m/s^2*
I_1	First moment of the area A about the free surface, *m^3*
K	Loss coefficient
m	Hydraulic mean depth, *m*
p	Pressure, *N/m^2*, *mmH_2O* or *mH_2O*
P	Wetted perimeter, *m*
Q	Air or water flow rate, *m^3/s*
S_f	Friction slope
S_0	Pipe slope
t	Time, *s*
u	Mean air and water flow velocity, *m/s*
x	Distance, *m*
ρ	Fluid density, *kg/m^3*
γ	Ratio of specific heats
C^+,C^-	Characteristics in a x-t plane
$_{atm}$	Atmospheric conditions
$_J$	Pipe identifier
$_{local}$	Local node identifier
$_N$	Number of pipe inter-nodal sections
$_{P, R, S}$	Nodal identifiers in MoC calculation

1 INTRODUCTION

It is accepted that pressure surge, or pressure transient propagation, is a fundamental consequence of any change in a system's operating point. The severity of the transient, and its consequences, depend upon the rate of change imposed on the flow, the design of the system and its failure criteria. The potential for a surge event to lead to system failure is independent of the absolute pressure levels reached.

The need to recognise pressure transient phenomena within the fluid services associated with building operation has increased in importance with the complexity of the built environment. The need to simplify design while accommodating both enhanced user expectations and climate change, the latter paradoxically identifiable through the need for water conservation and the likelihood of increased rainfall intensity and frequency, provides the impetus to include unsteady flow simulation within system design.

Two contrasting systems will be discussed: the vent system that ensures that no foul gasses or contamination enters habitable space from the sewer and modern siphonic roof drainage systems designed to run full bore while draining large roof areas. In the first case failure is defined by air pressure excursions outwith ±375 N/m^2, while in the second the prevention of gutter overtopping and pipe implosion provide the design limits.

1.1 Operation of a building drainage and vent system

Building drainage and vent networks within large, complex buildings are intended to ensure the efficient removal of fluids and waste matter as well as ensuring that there is no ingress of contaminated air or sewer gases into habitable space from the sewer. A Victorian obsession, this latter design requirement led to the extremely complex drainage and vent pipework seen on UK buildings dating from the 19th and early 20th century.

The venting of building drainage networks has been a concern for well over a hundred years(1). Early venting featured individual appliance connections linked directly to the external atmosphere via dedicated vent stacks terminating above the building roof line. The need to minimise external pipework, due to both climatic considerations and the advent of taller buildings, led to a progressive reduction in vent complexity, evidenced in the UK by the introduction of the single stack system in the 1960s. Further reductions in venting provision were introduced from the mid 1980s with the introduction of local air admittance valves (AAVs), installed within the habitable space to allow inwards air pressure relief. Such valves close in response to positive pressures in the network in order to prevent odour ingress and possible cross contamination; an approach accepted in Europe and the UK but still opposed in the US and, to a lesser extent, Australia.

The annular water downflow in the system vertical stacks establish an entrained airflow whose magnitude depends on system design and the unsteady nature of the appliance discharges. Changes in waterflow result in changes in entrained airflow, these changes being propagated throughout the drainage and vent system as air pressure transients. While these transients are of low amplitude, 100 *mm* water gauge would be a severe transient, they may destroy the system protection against the ingress of contaminated air, provided by appliance water trap seals of 50 to

75 *mm* depth. Trap seal loss may occur as a result of either negative transient propagation, typically associated with increases in annular water downflow in the vertical stacks, or positive air pressure transients associated with interruptions to the entrained airflow through the network as a result of water flow surcharge.

The venting necessary within a complex multi-storey building drainage network establishes airflow paths from habitable space to either the external atmosphere or the sewer system. **Figure 1** shows the normal mode of operation and includes examples of a 'dry trap' that has lost sufficient water to allow gas movement into the network. Air is also naturally entrained by appliance operation. The prevailing pressure regime within the system is principally negative, thereby providing a 'safe' exit route for the air through the sewer connection.

However, the flow loading of the drainage network can give rise to positive pressure transients. The naturally cyclic nature of the occurrence of the water curtain at the base of the vertical stack, or at an offset, results in entrained airflow stoppage and may be sufficient to establish a contamination path through a depleted or compromised trap. Flow surcharge at these locations may also interrupt the entrained airflow and lead to positive transient propagation. **Figure 2** illustrates this effect and demonstrates that the resultant positive pressure wave, generated when the entrained air path is closed, introduces the potential for gases to exit into habitable space via a depleted trap.

The unsteady nature of the driving waterflow, coupled to the possibility that the entrained airflow path may be closed with undetermined frequency and duration, leads to a requirement to model the transient behaviour of building drainage vent systems. The introduction of a transient analysis allows the effect of serial events, essential prerequisites for a system failure, such as appliance discharge followed by system surcharge, to be investigated for the first time.

The mechanism by which entrained airflow is established within drainage and vent systems is well understood, **Figure 3**. The annular water flows present in the 'wet' stack entrains airflow due to the condition of 'no slip' established between the annular water and air core surfaces. This results in the expected pressure variation down a vertical stack, falling from atmospheric above the stack entry, due to friction and the effects of drawing air through the water curtains formed at discharging branch junctions. Within the lower wet stack region the pressure recovers to above atmospheric due to the traction forces exerted on the airflow and the necessity to discharge air to the downstream drain through the water curtain formed at the stack base. These mechanisms may be used as a basis for a finite difference method of characteristics (MoC) simulation of air entrainment provided that the relationships linking applied water to entrained airflow are known, together with the influence of stack diameter, roughness and building height.

The analysis presented is based on the established approach reported at all eight earlier Pressure Surge Conferences. The techniques proposed, based on the solutions introduced in the 1960s[2,3], have been applied by the authors to free surface drainage flows as well as entrained airflows and waterhammer[4,5]. However the application to drainage vent systems is novel as the driving terms are distributed over the whole height of the 'wet' stack rather than being represented by a pump or reservoir boundary. The relationships defined by Jack[6], **Figure 3**, allow the AIRNET simulation to predict air transient propagation by introducing a pseudo friction factor applicable between the annular water film and the air core, thus providing a modelling of the traction force exerted on the entrained air. Jack[7] proposed that, by summing each of the defining pressures within a vertical stack system, i.e. absolute pressure values below each active branch and the back pressure at the base water curtain, the 'traction work done' by the falling annular water film could be calculated. Based on extensive experimental data this approach allows the definition of a 'pseudo friction factor' applicable in the wet stack and operable across the water annular flow/entrained air core interface. The most important outcome is that predictions need not now be limited to single point discharge. Through the use of a variable friction factor term, combined discharge flows, and their effect on the entrainment of air, can now be modelled. It will be appreciated that the airflow entrained in the lower levels of the wet stack may exceed that appropriate to the annular water flows present at the upper levels.

The variable friction factor allows the lower level annular flow to provide airflow entrainment and hence a rising air pressure. In the upper levels this air is effectively drawn down past a slower moving water film that impedes its entrainment, and leads to an observed reduction in air core pressure levels. When linked to a MoC solution this approach therefore provides a general simulation applicable across the whole range of vent system design.

1.2 Operation of siphonic roof drainage

Siphonic roof drainage systems have been in existence for approximately 30 years, and are becoming an increasingly common element of the urban drainage infrastructure. In that time, the construction industry in most developed countries has been gradually persuaded of the benefits that these systems offer when compared to conventional roof drainage technologies. In contrast to conventional systems, siphonic roof drainage depends upon the purging of air from the system (priming) and the subsequent establishment of full bore flow conditions within the pipework connecting the outlets in the roof gutters to the downstream surface water sewer network (at ground level). The priming of a typical siphonic system, **Figure 4**, may be summarised as:

1. Full bore flow conditions form at some point within the horizontal pipework
2. Full bore flow conditions propagate downstream (towards the vertical downpipe) and upstream (towards the gutter outlets).
3. Full bore flow conditions reach the vertical downpipe, and the system starts to depressurise as the downpipe fills.
4. Once the conditions throughout the downpipe are full bore, any remaining air pockets are purged from the system and full siphonic action occurs.

Current design practice assumes that, for a specified design storm, a siphonic system fills and primes rapidly with 100% water. This assumption allows siphonic systems to be designed utilising steady state hydraulic theory. The steady flow energy equation is normally employed[8], with the elevation difference between the gutter outlets and the point of discharge being equated to the head losses in the system. Although this approach neglects the small quantities of entrained air that always enter a siphonic roof drainage system, it has been reported to yield operational characteristics similar to those observed in laboratory test rigs at the fully primed state[8,9].

However, steady state design methods are not applicable when a siphonic system is exposed to a rainfall event below the design criteria or an event with time varying rainfall intensity. In both of these cases, the flow may contain substantial quantities of entrained air and exhibit pulsing or cyclical phases; a result of greatly varying gutter water levels and an indication of truly unsteady, transient flow conditions. Such problems are exacerbated when the system incorporates more than one outlet connected to a single downpipe (multi-outlet system), as the breaking of full bore conditions at one of the outlets (due to low gutter depths and air entry) is transmitted throughout the system and, irrespective of the gutter depths above the remaining outlet(s), results in cessation of siphonic conditions. As sub-design events are the norm, it is clear that current design methods may not be suitable for determining the day-to-day performance characteristics of siphonic roof drainage systems. This is a major disadvantage, as it is during these events that the majority of operational problems tend to occur, e.g. noise and vibration. In addition to these types of everyday operational issues, a number of more serious problems are known to have occurred with siphonic roof drainage systems; experience has shown that such catastrophic failures are normally a result of blockages to one of the outlets, leading to decreased system capacities, the generation of negative pressure transients and, in extreme cases, system failure due to pipe implosion(10).

In response to perceived deficiencies in current design practice, a siphonic roof drainage research programme was initiated at Heriot-Watt University in 1996. This has led to a better understanding of the performance characteristics of siphonic systems, and the development of a numerical model (SIPHONET) capable of accurately simulating the operation of such systems under a number of different operational scenarios. The analysis presented herein illustrates the use of this model as a diagnostic design tool, with particular reference to transient analysis.

2 BASIS FOR MATHEMATICAL MODELS

The solution technique for both applications involves the use of the MoC for full bore flow conditions, with a Lax Wendroff based technique being applied to model the initial free surface conditions present in siphonic roof drainage systems at the onset of a rainfall event.

2.1 Simulation of drainage vent systems and odour paths

The equations of continuity and momentum for the case of low amplitude air pressure transient propagation may be expressed as:

$$c^2 \frac{\partial u}{\partial x} + \frac{2}{(\gamma - 1)} c \left(\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} \right) = 0 \qquad \textbf{[1]}$$

$$\frac{2}{(\gamma - 1)} c \frac{\partial c}{\partial x} + \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{fu|u|}{2m} = 0 \qquad \textbf{[2]}$$

These relationships are a pair of quasi-linear hyperbolic partial differential equations that are amenable to finite difference solution once transformed via the MoC into the finite difference relationships (equations 3 to 6). These relationships link conditions at a node one time step in the future (P) to current conditions at adjacent upstream and downstream nodes (R and S). For the C^+ characteristic:

$$u_P - u_R + \frac{2}{\gamma - 1}(c_P - c_R) + 4 f_R u_R \,|\, u_R \,|\, \frac{\Delta t}{2D} = 0 \qquad \textbf{[3]} \qquad \text{when} \qquad \frac{dx}{dt} = u + c \qquad \textbf{[4]}$$

And for the C^- characteristic:

$$u_P - u_S - \frac{2}{\gamma - 1}(c_P - c_S) + 4f_S u_S \mid u_S \mid \frac{\Delta t}{2D} = 0 \qquad \textbf{[5]} \qquad \text{when} \qquad \frac{dx}{dt} = u - c \qquad \textbf{[6]}$$

where wave speed c is given by: $$c = \left(\frac{\gamma p}{\rho}\right)^{0.5} \qquad \textbf{[7]}$$

[Note that f_R and f_S are functions of time, location and annular water downflow and hence act as drivers in the simulation by generating the entrained air flow within the stack].

These equations are cast in terms of the air mean flow velocity and the local wave speed due to the interdependence of air pressure and density. Pressure at each node at each time step is given by:

$$p_{local} = [\ (p_{atm} / \rho_{atm})\ \ (\gamma/c^2_{local})^{\gamma}\ ]^{1/(1-\gamma)} \qquad \textbf{[8]}$$

In common with other MoC applications, only one characteristic equation exists at a boundary. Consequently, a boundary equation is required to link airflow conditions to applied water flow or other system parameters, such as the operating characteristics of an AAV or the airflow resistance of a water curtain.

At an open vent to atmosphere the boundary condition to be solved with the available C^+ characteristic is simply:

$$p_{(J,N+1)} = p_{atm} \qquad \textbf{[9]}$$

where $_J$ is the pipe identifier and $_{N+1}$ represents the terminal node of the pipe.

Similarly if the airflow path is closed then the boundary condition to be solved with either the available C^+ or C^- characteristic is provided by putting the local airflow mean velocity to zero:

$$u_{(J,1 \text{ or } J,N+1)} = 0 \qquad \textbf{[10]}$$

At an AAV, the boundary is expressed by zero local airflow if the line pressure is greater than a small negative threshold. However, if the pipe local air pressure is below the opening threshold of the AAV (effectively the suction pressure required to lift the valve diaphragm), then the boundary condition is provided by an airflow vs. valve loss coefficient expression of the form:

$$p_{(J,1)} - p_{atm} = KQ^2_{(J,1)} \qquad \textbf{[11]}$$

The value of the AAV loss coefficient K will also vary, decreasing as the diaphragm lifts until the valve is fully open and thereafter having a constant value.

In addition it is necessary to provide local calculation and substitution for the air/water friction or traction coefficients. Jack[7] provides substitution equations for the friction factor (f) in the wet stack; friction in the dry stack is fully represented by the expected application of standard relationships, e.g. the Colebrook-White friction formulation. Variations in applied water downflow therefore act directly through this frictional representation in the characteristic equations to generate an unsteady airflow regime. As the friction factors appear in the characteristic equations, changes in water flow conditions are introduced to the calculation of air core pressure and velocity, and hence transients may be generated and propagated throughout the network.

In general increasing water flows generate negative transients in as much as increasing water flows generate increased traction on the air core. In extreme conditions these negative transients may result in trap seal depletion due to induced siphonage. However surcharge of the stack, either at its base, at offsets or at discharging branches can cut off the air path down the stack. Airflow is thus brought to rest, possibly instantaneously. In these conditions positive transients are generated that can lead to trap seal depletion due to back pressure.

2.2 Simulation of siphonic rainwater systems

The continuity and momentum equations of one dimensional, unsteady flow in open channels may be written in conservative form as[11]:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad \textbf{[12]}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left[\frac{Q^2}{A}+gI_1\right]=gA\left(S_0-S_f\right) \qquad \textbf{[13]}$$

While the continuity and momentum equations of one dimensional, unsteady full bore flow may be written as[12]:

$$\rho c^2\frac{\partial u}{\partial x}+u\rho g\left[\frac{\partial p}{\partial x}+S_0\right]+\rho g\frac{\partial p}{\partial t}=0 \qquad \textbf{[14]}$$

$$u\frac{\partial u}{\partial x}+\frac{\partial u}{\partial t}+g\frac{\partial p}{\partial x}=g\left(S_0-S_f\right) \qquad \textbf{[15]}$$

Equations 12 to 14 form the basis of the SIPHONET model. As they are quasi-linear hyperbolic partial differential equations, they cannot be solved directly, and recourse must again be made to some form of numerical solution technique. Early model development utilised the MoC technique for both the free surface (initial) and the full bore (fully primed) flow conditions. However, it soon became apparent that the MoC technique was not particularly suited to the simulation of hydraulic jumps under the specific conditions occurring in multi-outlet siphonic systems. As the wide ranging movement of hydraulic jumps is an essential element of system priming, the MacCormack method[13] was employed to simulate the initial free surface flow conditions, whilst retaining the MoC technique for the simulation of full bore flow conditions.

The MacCormack solution technique is a variation of the classical Lax-Wendroff method, and it relies on the hyperbolic nature of the governing equations (equations 12 and 13), which leads to spontaneous discontinuities that have real physical meanings, e.g. hydraulic jumps. The technique is a non-centered, two step finite difference scheme which is second order accurate in time and space. Staring from the initial time level, where conditions are calculated at regular points throughout the system using standard steady state theory, the solution at the new time level is computed in a two step *predictor – corrector* process. The second order nature of the MacCormack method means that it generates spurious oscillations in the vicinity of hydraulic jumps; oscillations which have no real meaning, and are purely a numerical anomaly. One method of alleviating this problem is to add artificial viscosity to the solution scheme(11). In SIPHONET, the Jameson(14) artificial viscosity technique has been employed.

Although equations 12 and 13 have been derived specifically for free surface flow cases, utilisation of the Preissmann slot technique(12), **Figure 5**, means that they may also be applied to the short periods of pressurised, full bore flow conditions that occur within the horizontal pipework just before the vertical downpipe starts to fill. Ideally the width of the Preissmann slot should be such that the wave speed in the composite, and fictitious, pipe/slot section equals that which would occur in the actual pipe under the same conditions. However, this would yield an extremely narrow slot width, which would result in numerical instabilities and simulation failure. Consequently it is necessary to adopt a larger slot width, generally of the order of 1-5% of the pipe diameter. Although this approach introduces a small degree of computational error, it is considered the only feasible method of linking the free surface MacCormack model to the full bore MoC model.

As the vertical downpipe within a siphonic system starts to fill, the system will start to depressurise, thus rendering the MacCormack method unsuitable. At this point it is necessary to switch over to the classical MoC solution technique (as described previously for vent system analysis) of the governing equations of full bore flow (equations 14 and 15). When this occurs, SIPHONET checks for areas of the system where free surface conditions exist; it is these areas that correspond to the trapped air pockets observed during the experimental work. Once the system is primed, these air pockets are then tracked as they leave the system, their velocities being set equal to the that of the local water flows and their volumes/pressures being dependent on the local water pressure conditions and the gas laws. Depending on system layout, certain types of airpockets are assumed to become mixed with the water flow before exiting the system, hence forming the type of "bubbly flow" observed during the experimental work.

In common with the approach detailed previously for vent system analysis, it is necessary to supply additional information, in the form of boundary conditions, to allow the solution to proceed. When using either of the solution techniques detailed above, the conditions occurring at system boundaries (internal and external) are normally calculated by solving the available characteristics with a relationship relating pressure head to flow rate, although in the case of supercritical flow at pipe entry it is necessary to impose flow conditions. The majority of these relationships take the form of empirical formulae, derived from experimental data.

SIPHONET assumes that, once a system entry flows full bore, any flow entering the system is a homogeneous air/water mixture; the air content, and hence wave celerity, being a function of the gutter water depth. As there is no satisfactory, purely theoretical method of simulating the type of pulsing flow conditions that were observed during the experimental work under certain circumstances, SIPHONET represents these conditions by assuming full bore flow conditions with a high air content (based on the relative flow rates converging at the junction). To simulate the additional head losses incurred due to the pulsing nature of the flow, an increased pipe roughness value is utilised where pulsing flow conditions are present.

As the MacCormack method is not readily applicable to vertical pipework, the free surface flow conditions in the downpipe are assumed to be annular[15], whilst the filling of this pipework is simulated using a volumetric based technique. As well as tracking the progress of the full bore front in the vertical downpipe, SIPHONET also tracks the progress of any free surface fronts, and can hence simulate the draining of individual system branches or complete systems as rainfall intensities decrease. By utilising sharp crested weir theory[11], SIPHONET can also calculate the onset, and volumetric extent, of flooding due to gutter overtopping.

3 RELEVANCE OF SURGE ANALYSIS TO BUILDING AND ROOF DRAINAGE SYSTEMS

3.1 Cross contamination airflow prediction in a multi-storey building drainage and vent system

The case discussed below illustrates a typical application of the simulation to determine the risk of cross contamination in a building where airflow from an upper floor, entering the vent system through an AAV as well as through the stack roof termination, is predicted to exhaust into habitable space lower down the building via a depleted trap following a surcharge event at the base of the stack. Application of the MoC simulation yields information that would not otherwise be available to the designer and allows decisions to be made as to the advisability of the design and the venting solution chosen.

Figure 6 illustrates the airflow movement in the vent system in response to an annular water downflow that rises to 2 *l/s* over 2 *s* and then ceases 8 *s* into the simulation. Air is drawn into the stack through the roof termination and via the Level 6 AAV. Note that the valve diaphragm flutters, resulting in an intermittent air inflow via this route. The combined airflow exits the stack to the sewer connection.

Between 3.5 *s* and 4 *s* into the simulation the airflow is interrupted by a flow surcharge at the stack base. This generates a positive transient and reduces the exit airflow to the sewer to zero. As a result of the positive pressures generated in the stack, air is exhausted into the habitable space on Level 2 where the trap seal is compromised. **Figure 7** illustrates the air volumes involved, negative values indicate air entering the stack or the sewer, while positive values, or interruptions to the negative flow, indicate airflow into the habitable space or back to atmosphere via the roof termination.

Following dispersal of the surcharge **Figure 6** illustrates the airflow returning to the earlier condition. However it will be seen that the trap on Level 2 has failed as air is seen to continue to enter the stack via this route. Airflow continues for some time due to the inertia of the system.

Thus the simulation has been shown capable of dealing with a series of system operating conditions, namely ‘normal’ operation where the stack termination and the AAV act to alleviate the negative pressures in the system, followed by the response to the surcharge at the base of the stack. Finally the simulation predicts the continuing airpath through the depleted trap on the second floor. This level of design information is only accessible via the application of unsteady flow analysis.

3.2 Siphonic roof rainwater dynamic balancing and pipe implosion

The measured (laboratory experiments) and predicted (SIPHONET modelled) data discussed below relates to the siphonic system illustrated in **Figure 8**, which is a schematic of a laboratory test rig used during the development of the numerical model.

The data shown in **Figure 9** shows the measured and the predicted depths in gutter 1 (G1) and pressures in pipe 3 (P3) in response to a simulated rainfall event. In addition to showing the formation of siphonic conditions (0*s* – 32*s*) and a period of steady siphonic action (32*s* – 62*s*), this data also illustrates the rise in system pressures that is transmitted throughout the system when the depth in gutter 1 drops below that necessary for full bore flow, hence allowing air to enter the system and break the siphon (at approximately 62*s*). Clearly, if the inflow to gutter 1 was not restarted (at approximately 82*s*), siphonic action would not have been re-established and the continuing inflow to gutter 2 would have led to overtopping of that gutter, and hence system failure. It is also apparent from **Figure 9** that oscillations occur when the system starts to de-pressurise and the model switches from using the MacCormack solution technique to the MoC (at approximately 24*s*). These are due to the slight errors associated with use of the Preissmann slot technique, and they may be considered temporary 'adjustment' errors; a fact borne out by the accuracy of the model immediately prior to and immediately after this switch has occurred.

Figure 10a shows the measured and predicted pressures in pipe 2 (P2) when, under steady siphonic conditions, the outlet in gutter 2 (G2) is partial blocked and immediately re-opened. With reference to the predicted data, it can be seen that this results in the generation of a negative pressure transient (as P2 is downstream of the flow stoppage), the effects of which quickly dissipate as the blocked outlet re-opens almost immediately. The initial positive peaks and general "non-oscillatory" nature of the measured data is entirely due to the experimental blockage method employed (pushing an upturned container over the outlet), which resulted in water initially being forced into the outlet and the container acting as a small surge chamber.

Figure 10b shows the predicted pressure in pipe 2 (P2) in response to an instantaneous and total blockage to the outlet in gutter 2 (G2). This again results in the generation of a negative transient; as the simulated blockage was instantaneous and total, the pressure drop associated with this transient is equal to the Joukowsky pressure drop (ρcu , where u is the flow velocity destroyed due to the outlet blockage). Pressure transients of this magnitude would almost certainly result in the implosion of the type of pipework commonly employed in siphonic roof drainage systems.

4 CONCLUSIONS

The analysis of pressure surge through the solution of the St Venant equations has become an accepted technique. The application of these techniques to aid in system design and possible forensic analysis of system failures is now a more fruitful area of application. Those illustrated by this paper have been drawn from areas that might not have been thought of in the early development of the MoC solutions, however both illustrate the suitability of the surge analysis. The prevention of cross contamination of habitable space via the operation of the building drainage system is a fundamental requirement of drainage design for complex multi-storey buildings; the application illustrates the facility with which such a possibility may be predicted and hence avoided by careful design. Similarly, the benefits associated with siphonic roof drainage systems (lower costs, less obtrusive, more flexible), and the challenges posed by climate change, will lead towards a greater use of siphonic roof rainwater drainage. The analysis of such systems presented herein again illustrates the application of surge analysis for diagnostic design purposes and failure analysis.

5 REFERENCES

1. Wise A.F.E. and Swaffield J.A. (2002). *Water, Sanitary and Waste Services for Buildings (5th Edition)*. Butterworth Heinemann: Oxford.
2. Lister M. (1960). Numerical Simulation of hyperbolic partial differential equations by the Method of Characteristics. *Numerical Methods for Digital Computers*. Wiley: New York.
3. Streeter V.L. and Wylie E.B. (1967). *Hydraulic Transients*. McGraw-Hill: New York.
4. Swaffield J.A. and Boldy A. P. (1993). *Pressure surge in pipe and duct systems*. Avebury Technical: Aldershot.
5. Swaffield J.A., Ballanco J. and McDougall J.A. (2002). Pressure surge in building utility services exacerbated by the presence of trapped or entrained air. *Building Services Engineering Research and Technology*. Vol. 23, No. 3.
6. Jack L. B. (1997). *An investigation and analysis of the air pressure regime within building drainage vent systems*. Ph.D. Thesis. Heriot-Watt University.
7. Jack L.B. (2000). Developments in the definition of fluid traction forces within building drainage vent systems. *Building Services Engineering Research and Technology*. Vol. 21, No 4, pp 266 - 273.
8. May R.W.P. and Escarameia M. (1996). *Performance of siphonic drainage systems for roof gutters*. Report No SR 463. HR Wallingford.
9. Arthur S. and Swaffield J.A. (2001). Siphonic Roof Drainage: The State of the Art. *Urban Water*. Vol. 3, No. 1, pp. 43 - 52.
10. Bowler R. and Arthur S. (1999). Siphonic Roof Rainwater Drainage – Design Considerations. *Proceedings of Water Supply and Drainage for Buildings : CIB W62 1999*. Edinburgh.
11. Chaudhry M.H. (1993). *Open Channel Hydraulics*. Prentice-Hall: New York.
12. Chaudhry M.H. (1979). *Applied Hydraulic Transients*. Van Nostrand Reinhold: New York.
13. MacCormack R.W. (1971). Numerical solution of the interaction of a shock wave with a laminar boundary layer. *Proceedings of 2nd International Conference on Numerical Methods in Fluid Dynamics*. Berlin.
14. Jameson A., Schmidt E. and Turkel E. (1981). Numerical solutions of the Euler equations by finite volume methods using Runga-Kutta time stepping schemes. *Proceedings of AIAA 14th Fluid and Plasma Dynamics Conference*. Palo Alto, USA.
15. Swaffield J.A. and Galowin L.S. (1992). *The engineered design of building drainage systems*. Ashgate: UK.

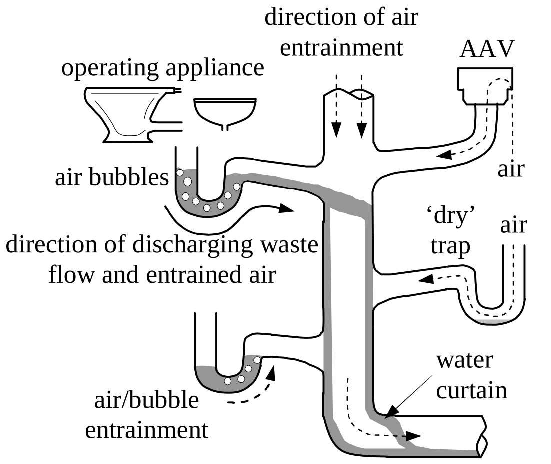


Figure 1. Operation of a building drainage and vent system

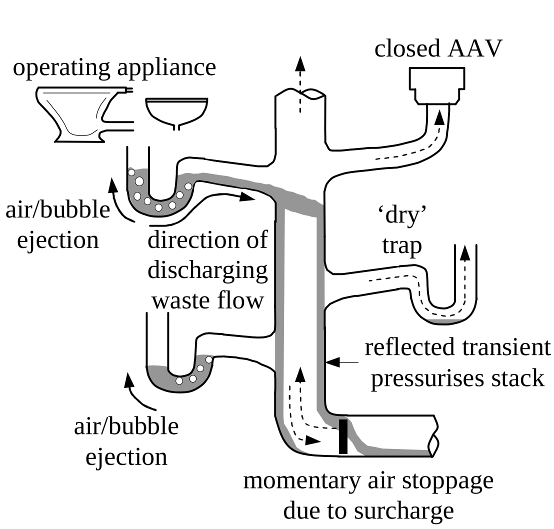


Figure 2. Route for cross contamination

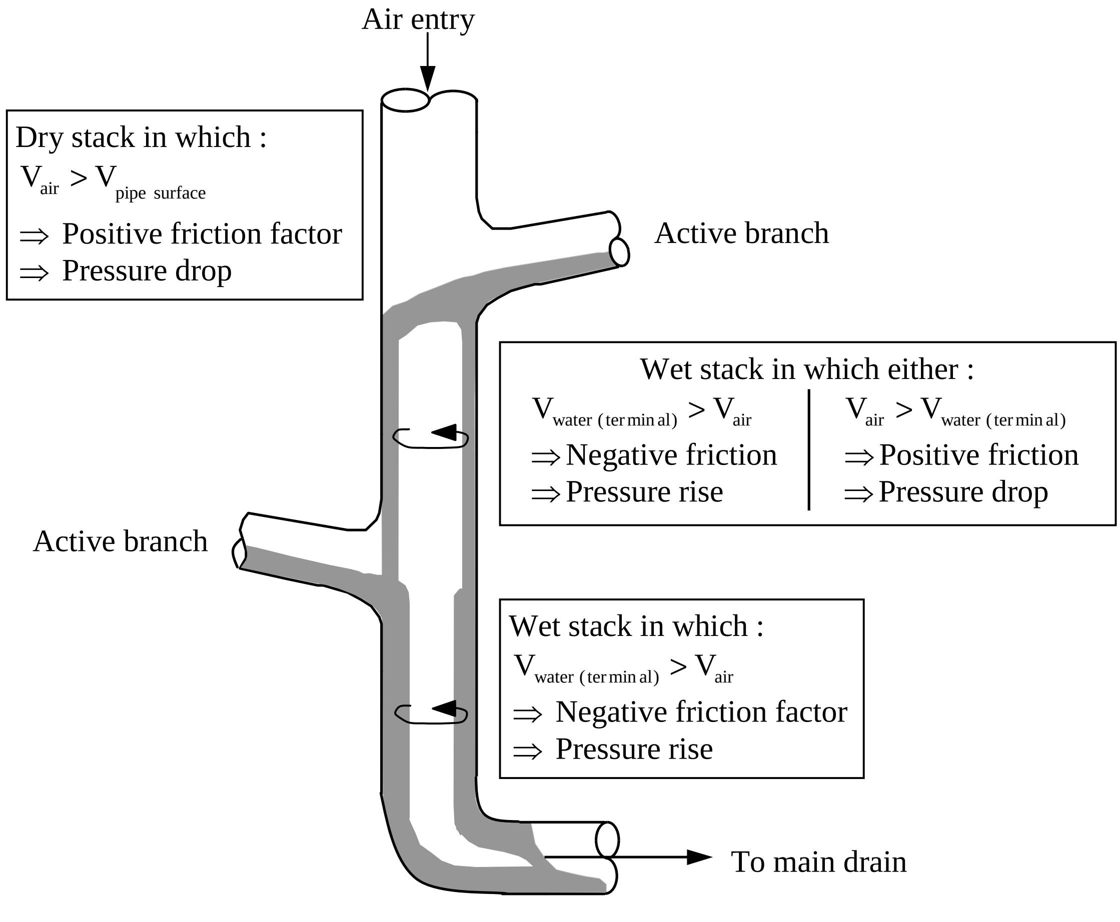


Figure 3. Mechanism of air entrainment in a building drainage system vertical stack

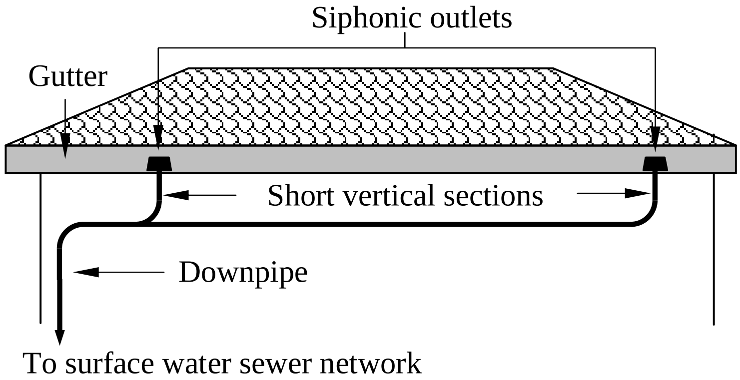


Figure 4. Typical siphonic roof drainage system

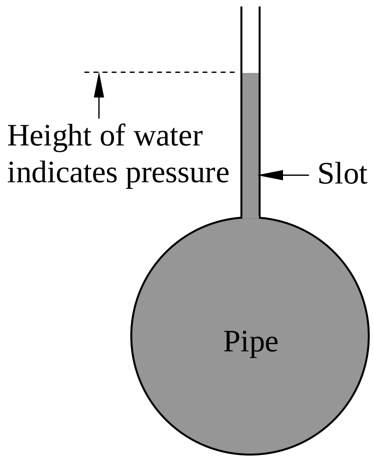


Figure 5. Preissmann slot

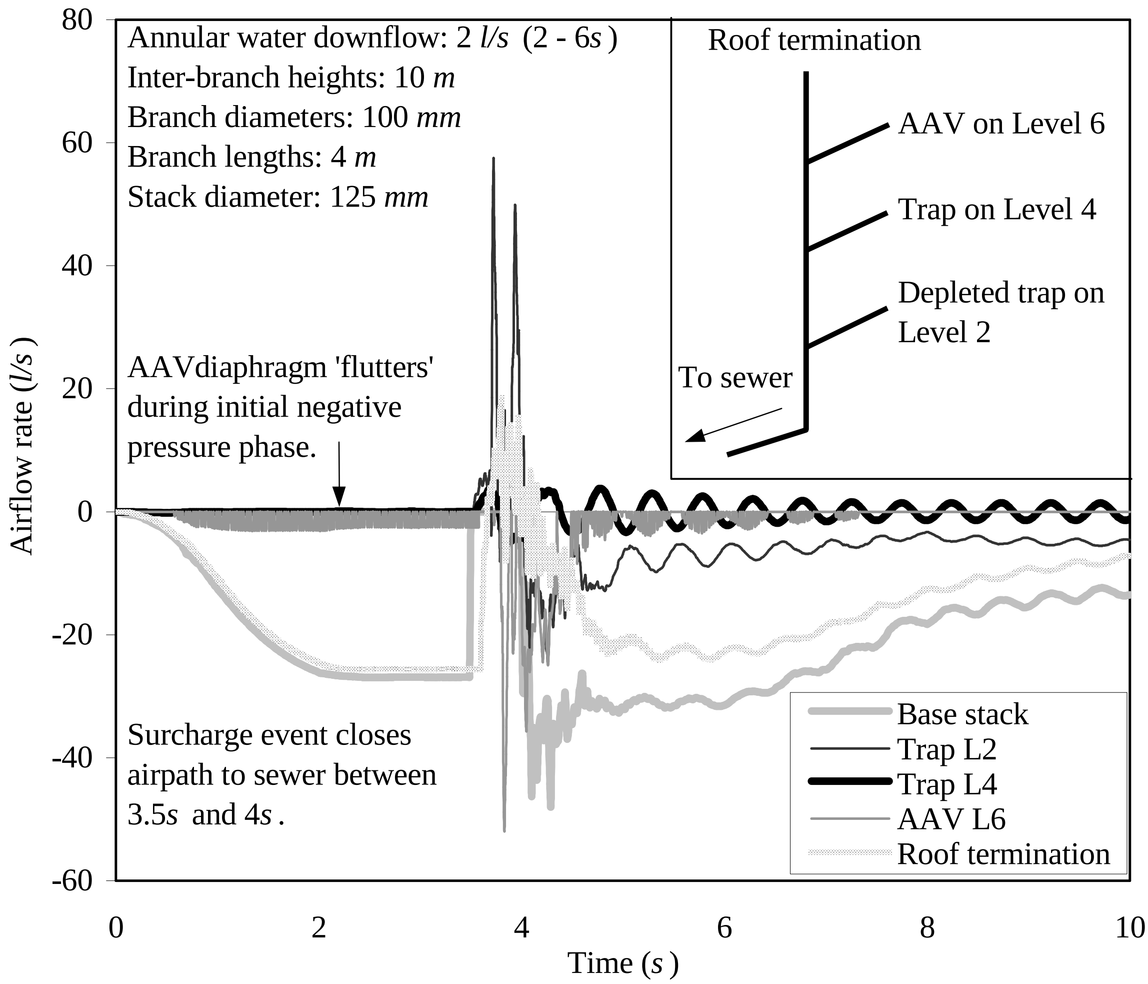


Figure 6. Airflow within the drainage vent system as predicted by the AIRNET simulation

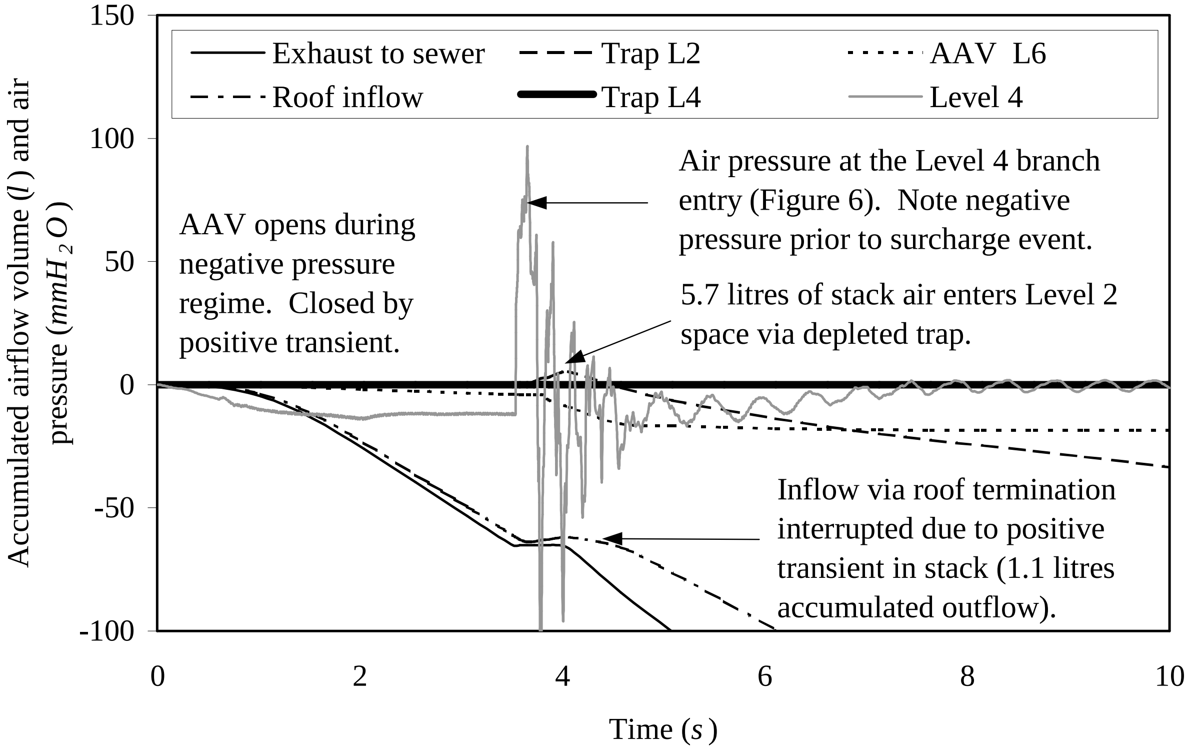


Figure 7. Accumulated cross contamination airflow and associated air pressure values within the stack

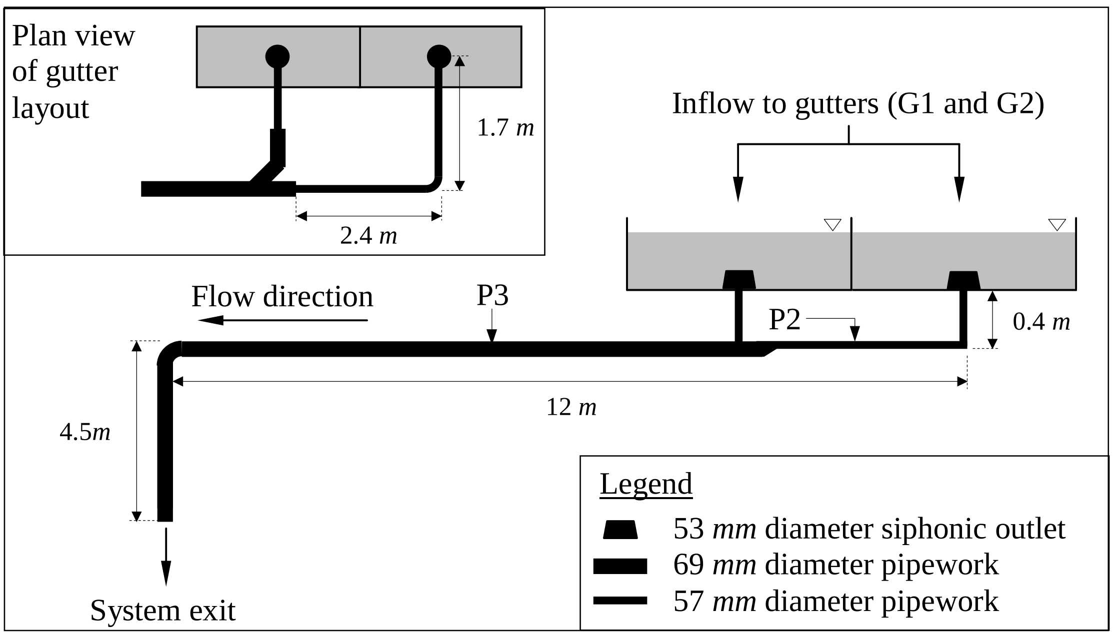


Figure 8. Schematic of experimental test rig

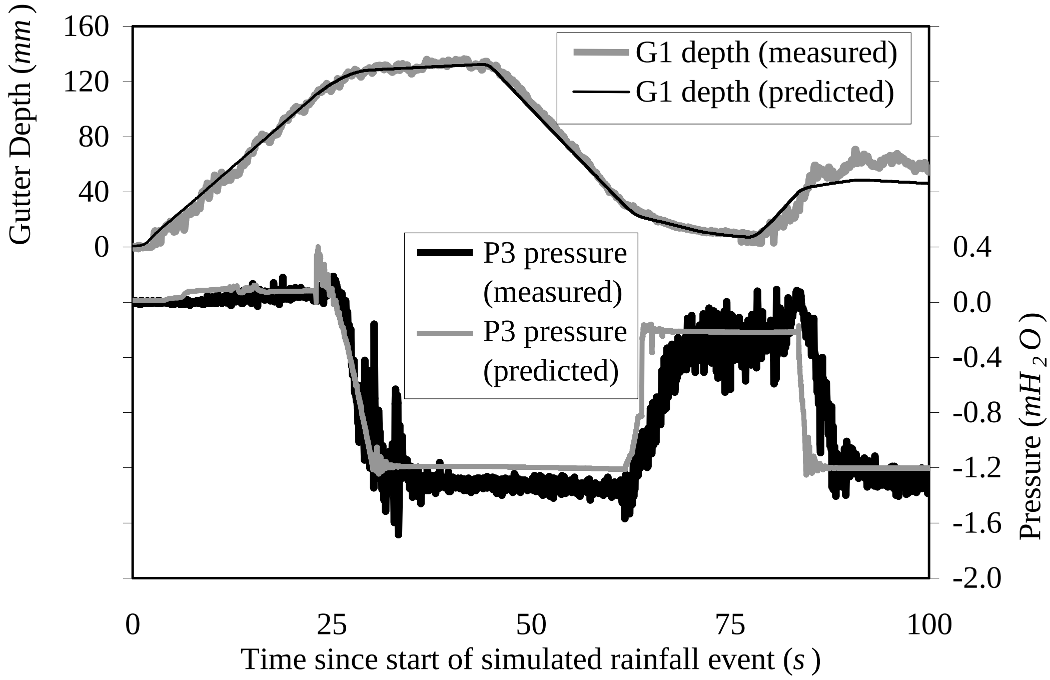
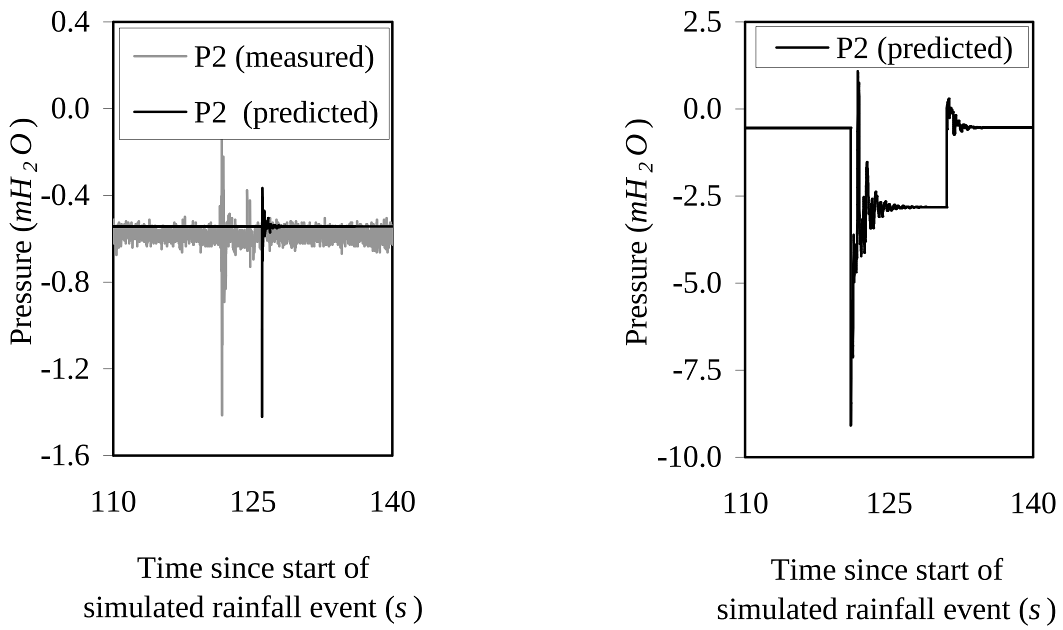


Figure 9. Measured and predicted gutter depths and system pressures: no inflow into gutter 1 between 62*s* and 82*s* (refer to Figure 8 for reference points G1 and P3)



a. Partial, temporary blockage ***b. Predicted instantaneous and total blockage***

Figure 10. Measured and predicted pressures when the outlet in gutter 2 was blocked and reopened (refer to Figure 8 for reference point P2)